Characterizing Fractured Rock: Hydrogeologic Conceptual Models of Ground-Water Flow and the Influence of Problem Scale

Allen M. Shapiro

U.S. Geological Survey, 431 National Center, Reston, VA 22092
Tel: 703-648-5884, FAX: 703-648-5274, e-mail: ashapiro@usgs.gov

Hydrogeologic Conceptual Models

The hydrogeologic characterization of contaminant migration and the design of ground-water restoration strategies in fractured rock sites must first focus on the spatial distribution of hydraulic properties. In particular, highly conductive fractures or geologic features in the rock need to be identified, along with the connectivity of these features. It is also necessary to identify the potential for fluid and chemical exhange between highly conductive features in the rock and the less conductive fractures and the primary porosity of the host rock. Once this characterization is conducted, the more vexing issues associated with the fate of toxic substances subject to various degradation processes can be addressed. The hydrogeologic conceptual model is the physical and chemical description of the fracture and matrix porosity of the rock and how the fractures and matrix porosity affect ground-water flow and chemical migration.

Fractured rock formations are hydrogeologically complex. Geologic structure and *in situ* stress fields control the occurrence of fractures, which are the predominant mechanism for fluid movement. No formation is uniformly fractured, and thus, assumptions of formation homogeneity and even anisotropy that are commonly applied in unconsolidated porous media may not be appropriate for the description of fluid movement in fractured rock. In addition, hydraulic conductivity of fractures can vary over many orders of magnitude in contrast to the range associated with unconsolidated geologic media. Also, because of complex geologic structures and fracture connectivity, hydraulic properties of fractured rock do not vary smoothly in space. It is not uncommon to observe abrupt spatial changes in the hydraulic properties in fractured rock with both depth and areal extent.

The complexities of fractured rock, however, often lead us to believe that there is little transfer value from one field site to the next. It is often assumed that the approach to charactertization and the development of hydrogeologic conceptual models of ground-water flow and chemical transport at one fractured rock site do not necessarily provide a direction for characterization at other field sites, even within a similar geologic setting.

Conceptual Similarities in the Spatial Configuration of Hydraulic Properties

Investigations at several fractured rock sites show that there are similarities in the types of fractures that exist in similar types of rock that have been subject to different types of geologic conditions and regional and local stress fields. For example, fractures observed in granite and schist in central New Hampshire exhibit similar characteristics to fractures observed in igneous intrusions and the metamorphic country rock, respectively, in the Piedmont region in Maryland. Also, bedding plane partings in the Silurian dolomite in parts of Illinois, Wisconsin and New York tend to control ground water flow. Similar hydrogeologic controls are observed in the bedded sandstones and shales in the Newark Basin in New Jersey.

In addition to similarities in the types of fractures observed in different geologic settings, there are similarities in the spatial configuration of highly conductive fractures. Similarities were observed not only within similar geologic settings, but also across different geologic conditions (Shapiro and Hsieh, 2001). A survey of time-drawdown records from aquifer tests conducted in bedded sedimentary rocks, such as dolomite, sandstone and shale, and in glaciated and unglaciated igneous and metamorphic rocks has shown unexpected similarities. The tests were conducted with a single highly permeable fracture or fracture zone isolated in the pumped borehole, and monitored intervals in observation boreholes had either one or no highly permeable fractures or fracture zones. This was accomplished using boreholes with open intervals at selected elevations or with packers isolating discrete intervals in the pumped and observation boreholes. The results of these aquifer tests showed that multiple monitored intervals in different observation boreholes had essentially the same time-drawdown history regardless of their distance to the pumped interval.

This type of aquifer test response would be anticipated in bedded sedimentary rocks, where bedding plane partings act as highly permeable zones that are connected hydraulically by fractures in the massive rock between bedding planes. Observation boreholes intersecting a given bedding plane during aquifer testing respond similarly because of the high permeability within the bedding plane. Aquifer tests conducted in the Silurian dolomite in New York and Illinois, and in the sandstone and shale beds of formations in the Newark Basin serve as examples.

In igneous and metamorphic rocks, in both glaciated and unglaciated terrain, fracturing tends to be considerably more complex than in sedimentary rocks, however, the aquifer test response of observation intervals also showed groups of monitored intervals in observation boreholes with nearly identical drawdown responses. Aquifer tests conducted in the igneous and metamorphic rock in New Hampshire and Georgia, and igneous rock in Sweden and Switzerland serve as examples. A detailed investigation at a bedrock site in central New Hampshire suggest that highly permeable fractures of various orientations form subhorizontal zones that are embedded within a network of less permeable fractures.

The similarity of drawdown responses in monitored intervals of observation boreholes regardless of distance to the pumped borehole suggests a model of aquifer heterogeneity where areally extensive, highly permeable zones are hydraulically connected by rock with less permeable fractures. Interpretation of these aquifer tests can be conducted by hypothesizing zones of high permeability embedded in a less permeable aquifer material, the hydraulic properties of which can be estimated by methods of parameter estimation used in conjunction with standard ground-water flow models.

The Influence of Problem Scale

At fractured rock sites that are the subject of a hydrogeologic characterization of contaminant migration over dimensions of 10's to 100's of meters, it is also necessary to consider the potential for ground-water flow and chemical migration over much larger distances. The potential for chemical migration over larger dimensions is especially acute at sites that have been subject to contaminant sources over extended periods of time, or at sites where contamination has not been addressed for extended periods of time. Because of the extreme variability in hydraulic properties and the complex connectivity of fractures, formation properties that govern fluid movement and chemical transport may vary as a function of the physical dimensions of the problem. The fractured rock in the Mirror Lake watershed in central New Hampshire has been one of the only fractured rock field sties where detailed investigations of ground-water flow and chemical migration have been conducted over dimensions that range from meters to kilometers.

Mirror Lake Site

The Mirror Lake watershed has been a site of multidisciplinary and multiscale investigations of ground-water flow and chemical transport in fractured rock (Hsieh *et al.* 1993; Shapiro *et al.* 1999). In the Mirror Lake area, bedrock is overlain by glacial drift, which varies in thickness from 0 to approximately 50 meters. The bedrock is primarily schist that has been extensively intruded by granite. Samples of granite and schist have porosities that range from 1 to 2 percent (%) (Wood *et al.* 1996); however, fractures are the primary conduits of ground-water flow.

Hydraulic Conductivity From Meters to Kilometers

The hydraulic conductivity of fractures and the bulk hydraulic conductivity of large volumes of rock were estimated from interpretations of hydraulic tests. Single-hole hydraulic tests were conducted in over 30 bedrock boreholes using a straddle-packer apparatus to isolate closely spaced fractures in boreholes (Shapiro and Hsieh 1998). The hydraulic conductivity of fractures as estimated from the single-hole tests ranges from the detection limit of the *in situ* equipment, which is approximately 10^{-10} meters per second (m/s), to 10^{-4} m/s (Shapiro and Hsieh 1998).

Hsieh and Shapiro (1996) and Hsieh *et al.* (1999) conducted several multiple-hole hydraulic tests by pumping water from a packed-off interval of one bedrock borehole and monitoring the fluid pressure in drift piezometers and packed-off intervals in bedrock boreholes distributed over approximately a hectare. The interpretation of these tests indicated that highly permeable fractures form subhorizontal zones that have lateral dimensions of 20-50 m; however, the fractures that comprise these zones are not subhorizontal. The zones of highly permeable fractures are connected hydraulically through a network of less permeable fractures. The network of less permeable fractures controls the bulk hydraulic conductivity of the rock, which is approximately 10^{-7} m/s, about 3 orders of magnitude less than the hydraulic conductivity of the most permeable fractures in the rock volume.

Over approximately 16 square kilometers in the Mirror Lake area, the bulk hydraulic conductivity of the rock was estimated using a regional ground-water flow model. The measured hydraulic head in bedrock boreholes and piezometers in the glacial drift, and the measured ground-water discharges to streams were used for model calibration (Tiedeman *et al.* 1998). The bulk hydraulic conductivity of the bedrock from the regional ground-water flow model was the same order of magnitude as the bulk hydraulic conductivity as estimated from aquifer tests that affected approximately a hectare. This indicates that conductive fractures are not controlling ground-water flow over dimensions of the watershed, and the bulk hydraulic conductivity of the rock in the Mirror Lake area does not change as a function of the problem scale (Hsieh 1998).

Dispersivity and Matrix Diffusion From Cores to Kilometers

Dispersivity is a measure of the variability in the fluid velocity affecting the advection of dissolved constituents in ground water (Gelhar *et al.* 1992), and matrix diffusion is usually described as the process by which dissolved constituents diffuse into or out of the primary porosity of the rock. In general, the diffusion coefficient for a nonsorbing species in the primary porosity of the rock is described by the following equation,

$$D = n_{rm}\, \alpha\, D_w = n_{rm}\, D_{rm}$$

where D is the formation diffusion coefficient, n_{rm} is the primary porosity of the rock, α is a formation factor related to the tortuosity and interconnectivity of the primary porosity, D_w is the diffusion coefficient of the dissolved constituent in water, and D_{rm} is the effective diffusion coefficient of the dissolved constituent in the rock. The dispersivity and the effective matrix diffusion were estimated from the interpretation of controlled laboratory and field-scale tracer tests, and the interpretation of concentrations of environmental tracers in ground water.

In diffusion experiments conducted in samples of granite and schist from the Mirror Lake area, Wood *et al.* (1996) used Cesium-137 (^{137}Cs) as a tracer. ^{137}Cs is highly retarded; however, once the retardation was considered, the effective diffusion coefficient, D_{rm}, was similar in magnitude to results of tracer tests conducted in similar types of rock (Ohlsson and Neretnieks 1995). In general, D_{rm} varies from 10^{-13} to 10^{-11} square meters per second (m^2/s). In the rock matrix, there is no ground-water flow, thus, chemical diffusion is the only mechanism for chemical migration, and dispersion is not considered.

Tracer tests were conducted between bedrock boreholes under hydraulically stressed conditions by pumping from a packed-off interval in one borehole and injecting a tracer solution into a packed-off interval in a nearby borehole (Shapiro 1996; Becker and

Shapiro 2000). The tracer tests were conducted in a highly permeable subhorizontal zone intersected by multiple boreholes. Interpretation of these tracer experiments showed that the dispersivity was approximately 10% of the distance between the boreholes, and estimates of the effective diffusion coefficient, D_{rm}, were at least equal to or greater than the coefficient of diffusion for the dissolved constituent in water, which is several orders of magnitude larger than estimates of D_{rm} from the laboratory experiments conducted on rock samples.

In general, D_{rm} should not be greater than the diffusion coefficient of the dissolved species in water; however, for the *in situ* tracer experiments D_{rm} was estimated to provide a best fit with the measured tracer concentrations at the pumped well. The large effective matrix diffusion is hypothesized to be an artifact of the extreme variability in the hydraulic properties of the fractures (Shapiro 2001). Advection from highly permeable fractures to low permeability fractures results in chemical advection over a short distance in an extended period of time, before reemerging into a highly permeable fracture again. This process is analogous to a dissolved constituent diffusing into and out of an immobile fluid (such as that in the rock matrix), and thus, the process is analogous to diffusion (even though it stems from the variability in the fluid advection).

Over distances of kilometers, the concentrations of environmental tracers measured in ground water were used to estimate the transport properties in the bedrock. Shapiro (2001) interpreted the concentrations of tritium (^3H) and dichlorodifluoromethane (CFC-12) in water samples collected from packed-off intervals in bedrock boreholes and piezometers in the glacial drift throughout the Mirror Lake area. Shapiro (2001) showed that, D_{rm} was at least 10^{-8} m^2/s and the dispersivity was approximately 100 m, which is a fraction of the travel distance of regional scale transport. The large effective matrix diffusion over travel distances ranging from 100's of meters to kilometers is again hypothesized to be an artifact of the extreme variability in the hydraulic properties of the fractures (Shapiro 2001).

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